APPLICATION

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TITLE: LOW-LOSS PHOTONIC CRYSTAL WAVEGUIDE
HAVING LARGE CORE RADIUS

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LOW-LOSS PHOTONIC CRYSTAL WAVEGUIDE HAVING LARGE CORE RADIUS

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims priority to U.S. provisional patent applications 60/264,201

5   filed January 25, 2001 and 60/337,603 filed November 8, 2001, the contents of which are

incorporated herein by reference.

BACKGROUND

This invention relates to the field of dielectric optical waveguides and optical

telecommunications.

10   Optical waveguides guide optical signals to propagate along a preferred path or paths.

Accordingly, they can be used to carry optical signal information between different locations

and thus they form the basis of optical telecommunication networks. The most prevalent

type of optical waveguide is an optical fiber based on index guiding. Such fibers include a

core region extending along a waveguide axis and a cladding region surrounding the core

15   about the waveguide axis and having a refractive index less than that of the core region.

Because of the index-contrast, optical rays propagating substantially along the waveguide

axis in the higher-index core can undergo total internal reflection (TIR) from the core-

cladding interface. As a result, the optical fiber guides one or more modes of

electromagnetic (EM) radiation to propagate in the core along the waveguide axis. The

20   number of such guided modes increases with core diameter. Notably, the index-guiding

mechanism precludes the presence of any cladding modes lying below the lowest-frequency

guided mode. Almost all index-guided optical fibers in use commercially are silica-based in

which one or both of the core and cladding are doped with impurities to produce the index

contrast and generate the core-cladding interface. For example, commonly used silica optical

25   fibers have indices of about 1.45 and index contrasts of up to about 2-3% for wavelengths in

the range of 1.5 microns.

Signals traveling down an optical fiber slowly attenuate, necessitating periodic

amplification and/or regeneration, typically every 50-100 km. Such amplifiers are costly, and

are especially inconvenient in submarine cables where space, power sources, and

maintenance are problematic. Losses for silica-based optical fibers have been driven down to about 0.2 dB/km, at which point they become limited by the Rayleigh scattering processes. Rayleigh scattering results from microscopic interactions of the light with the medium at a molecular scale and is proportional to $\omega^4\rho$, where ω is the light frequency and ρ is the

5   material density, along with some other constants of the material.

In addition to loss, signals propagating along an optical fiber may also undergo nonlinear interactions. In an ideal linear material, light does not interact with itself—this is what allows a fiber to carry multiple communications channels simultaneously in separate wavelengths (wavelength-division multiplexing, or WDM), without interactions or crosstalk.

10   Any real optical medium (even vacuum), however, possesses some nonlinear properties. Although the nonlinearities of silica and other common materials are weak, they become significant when light is propagated over long distances (hundreds or thousands of kilometers) or with high powers. Such nonlinear properties have many undesirable effects including: self/cross phase modulation (SPM/XPM), which can cause increased pulse

15   broadening and limit bitrates; and afour-wave mixing (FWM) and stimulated Raman/Brillouin scattering (SRS/SBS), which induce crosstalk between different wavelength channels and can limit the number of achievable channels for WDM. Such nonlinearities are a physical property of the material in the waveguide and typically scale with the density of the waveguide core.

20   Typically, optical fibers used for long-distance communications have a core small enough to support only one fundamental mode in a desired frequency range, and therefore called "single-mode" fibers. Single mode operation is necessary to limit signal degradation caused by modal dispersion, which occurs when a signal can couple to multiple guided modes having different speeds. Nonetheless, the name "single-mode" fiber is something of a

25   misnomer. Actually, single-mode fibers support two optical modes, consisting of the two orthogonal polarizations of light in the fiber. The existence and similarity of these two modes is the source of a problem known as polarization-mode dispersion (PMD). An ideal fiber would possess perfect rotational symmetry about its axis, in which case the two modes would behave identically (they are "degenerate") and cause no difficulties. In practice,

30   however, real fibers have some acircularity when they are manufactured, and in addition there are environmental stresses that break the symmetry. This has two effects, both of which

occur in a random and unpredictable fashion along the fiber: first, the polarization of light rotates as it propagates down the fiber; and second, the two polarizations travel at different speeds. Thus, any transmitted signal will consist of randomly varying polarizations which travel at randomly varying speeds, resulting in PMD: pulses spread out over time, and will

5   eventually overlap unless bit rate and/or distance is limited. There are also other deleterious effects, such as polarization-dependent loss. Although there are other guided modes that have full circular symmetry, and thus are truly "singlet" modes, such modes are not the fundamental modes and are only possible with a core large enough to support multiple modes. In conventional optical fibers, however, the PMD effects associated with the

10   fundamental mode of a small core supporting only a "single-mode" are far preferable to the effects of modal dispersion in a larger core multi-mode fiber.

Another problem with directing optical signals along an optical waveguide is the presence of chromatic or group-velocity dispersion in that waveguide. Such dispersion is a measure of the degree to which different frequencies of the guided radiation propagate at

15   different speeds (i.e., group velocities) along the waveguide axis. Because any optical pulse includes a range of frequencies, dispersion causes an optical pulse to spread in time as its different frequency components travel at different speeds. With such spreading, neighboring pulses or "bits" in an optical signal may begin to overlap and thereby degrade signal detection. Thus, absent compensation, dispersion over an optical transmission length places

20   an upper limit on the bit-rate or bandwidth of an optical signal.

Chromatic dispersion includes two contributions: material dispersion and waveguide dispersion. Material dispersion comes from the frequency-dependence of the refractive index of the material constituents of the optical waveguide. Waveguide dispersion comes from frequency-dependent changes in the spatial distribution of a guided mode. As the spatial

25   distribution of a guided modes changes, it sample different regions of the waveguide, and therefore "sees" a change in the average index of the waveguide that effectively changes its group velocity. In conventional silica optical fibers, material dispersion and waveguide dispersion cancel each other out at approximately 1310 nm producing a point of zero dispersion. Silica optical fibers have also been modified to move the zero dispersion point to

30   around 1550 nm, which corresponds to a minimum in material absorption for silica.

Unfortunately, while operating at zero dispersion minimizes pulse spreading, it also enhances nonlinear interactions in the optical fiber such as four wave mixing (FWM) because different frequencies remain phase-matched over large distances. This is particularly problematic in wavelength-division multiplexing (WDM) systems where multiple signals are carried at different wavelengths in a common optical fiber. In such WDM systems, FWM introduces cross talk between the different wavelength channels as described above. To address this problem, WDM systems transmit signals through optical fibers that introduce a sufficient dispersion to minimize cross-phase modulation, and thereafter transmits the signals through a "dispersion compensating fiber" (DCF), to cancel the original dispersion and minimize pulse spreading in the compensated signal. Unfortunately, aggregate interactions between the dispersion and other nonlinear processes such as self-phase modulation can complicate dispersion compensation.

Another type of waveguide fiber, one that is not based on TIR index-guiding, is a Bragg fiber, which includes multiple dielectric layers surrounding a core about a waveguide axis. The multiple layers form a cylindrical mirror that confines light to the core over a range of frequencies. The multiple layers form what is known as a photonic crystal, and the Bragg fiber is an example of a photonic crystal fiber. Some researchers have commented that Bragg fibers are not feasible for long distance optical transmission (see N.J. Doran and K.J. Blow, J. of Lightwave Tech., **LT-1**:588, 1983).

SUMMARY

The invention features a photonic crystal fiber having properties particularly suitable for use in optical transmission. In particular, the photonic crystal fibers described herein have low losses, exhibit small nonlinear effects, and can effectively operate in a non-degenerate single mode.

The inventors have recognized that designing a photonic crystal fiber (such as a Bragg fiber) with a large core radius (e.g., larger than about twice the wavelength of the guided radiation) leads to many desirable properties. For example, the inventors have determined that the fraction of energy outside of the core for a guided mode in a photonic crystal fiber scales inversely with the cube of the core radius. Accordingly, radiation and dissipation losses associated with the dielectric confinement layers can be made very small

by increasing the core radius. Moreover, because the confinement mechanism is not based on total internal reflection (TIR), the core material is not limited to a material having a relatively high index. Thus, the core material can be selected to minimize losses and nonlinearities. For example, the fiber may have a hollow core. Furthermore, the inventors

5   have discovered that confinement in the core is further improved by selecting materials for the layers (or regions) outside the core to have a large contrast in refractive index. Such contrasts are possible because the large core radius makes dissipation by the outside layers (or regions) less of an issue and thus the constituent materials of the outside layers (or regions) can be selected more on the basis of providing the desired index contrast, than on

10   absorption losses.

The inventors have further recognized that although the large core leads to multiple guided modes, the multiple modes have attenuation losses that differ significantly from one another. The differential losses among the multiple modes (i.e., modal filtering) rapidly lead to single-mode operation for modest transmission lengths, and thus modal dispersion is

15   avoided. Moreover, the lowest-loss mode can be selected to be non-degenerate, which eliminates effects such as polarization-mode dispersion. Nonetheless, the inventors have also recognized that there is an upper limit on the core size. When the core size is too large (e.g., larger than about forty times the wavelength of the guided radiation), the modes become closely spaced, and thus perturbations more easily cause coupling between different modes.

20   Also, the inventors have recognized that in Bragg fibers, the TE_{01} mode has a node near the core/cladding interface, which leads to a reduction in losses and nonlinear effects.

We will now summarize different aspects, features, and advantages of the invention.

In general, in one aspect, the invention features an optical waveguide including: (i) a dielectric core region extending along a waveguide axis; and (ii) a dielectric confinement

25   region surrounding the core about the waveguide axis, the confinement region including a photonic crystal structure having a photonic band gap, wherein during operation the confinement region guides EM radiation in at least a first range of frequencies to propagate along the waveguide axis. The core has an average refractive index smaller than about 1.3 for a frequency in the first range of frequencies, the core has a diameter in a range between

30   about 4λ and 80λ, wherein λ is a wavelength corresponding to a central frequency in the first

frequency range, and the dielectric confinement region extends transversely from the core for at least a distance of about 6λ.

In general, in another aspect, the invention features an optical waveguide including: (i) a dielectric core region extending along a waveguide axis; and (ii) a dielectric
5   confinement region surrounding the core about the waveguide axis. The confinement region has an average index greater than that of the core, and during operation the confinement region guides EM radiation in at least a first range of frequencies to propagate along the waveguide axis. The core has an average refractive index smaller than about 1.3 for a frequency in the first range of frequencies, the core has a diameter in a range between about
10   4λ and 80λ, wherein λ is a wavelength corresponding to a central frequency in the first frequency range, and the dielectric confinement region extends transversely from the core for at least a distance of about 6λ

In general, in another aspect, the invention features an optical waveguide including: (i) a dielectric core region extending along a waveguide axis; and (ii) a dielectric
15   confinement region surrounding the core about the waveguide axis. The confinement region includes alternating layers of at least two dielectric two materials surrounding the core about the waveguide axis, the two dielectric materials having refractive indices that differ by at least 10%, and wherein during operation the confinement region guides EM radiation in at least a first range of frequencies to propagate along the waveguide axis. The core has an
20   average refractive index smaller than about 1.3 for a frequency in the first range of frequencies, the core a diameter in a range between about 4λ and 80λ, wherein λ is a wavelength corresponding to a central frequency in the first frequency range, and the dielectric confinement region extends transversely from the core for at least a distance of about 6λ.

25   In general, in another aspect, the invention features an optical waveguide including: (i) a dielectric core region extending along a waveguide axis; and (ii) a dielectric confinement region surrounding the core about the waveguide axis. The confinement region includes at least 12 pairs of alternating layers of dielectric material having different refractive indices, wherein the layers are sufficient to guide EM radiation in at least a first range of
30   frequencies to propagate along the waveguide axis. The refractive indices of the alternating layers differ by at least 10% for a frequency in the first range of frequencies. At least some

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of the pairs of alternating layers have a total thickness equal to about a, and the core has a diameter in a range between about $10a$ and $100a$. In some embodiments, the core diameter is in a range between $20a$ and $80a$.

In another aspect, the invention features an optical waveguide including: (i) a dielectric core region extending along a waveguide axis; and (ii) a dielectric confinement region surrounding the core about the waveguide axis. The confinement region guides EM radiation in at least a first range of frequencies to propagate along the waveguide axis. The core has an average refractive index smaller than about 1.3 for a frequency in the first range of frequencies, and the core has a diamater in a range between about 5 microns and 170 microns.

In general, in another aspect, the invention features an optical waveguide including: (i) a dielectric core region extending along a waveguide axis; and (ii) a dielectric confinement region surrounding the core about the waveguide axis. The confinement region includes at least two dielectric materials forming a photonic crystal structure having a photonic band gap, the dielectric materials sufficient to guide EM radiation in at least a first range of frequencies to propagate along the waveguide axis. The refractive indices of the dielectric materials in the confinement region differ by at least 10% for a frequency in the first range of frequencies, and the core has a diameter in a range between about 5 microns and 170 microns.

Embodiments of any of the waveguides described above may include any of the following features.

The dielectric confinement region may extend transversely from the core for at least a distance of about 8λ, about 10λ, or about 12λ. The average refractive index of the core may smaller than about 1.3, smaller than about 1.2, or smaller than about 1.1 for a frequency in the first range of frequencies. The core may include a gas.

The diameter of the core may be in a range have a lower limit of any of 4λ, 6λ, 8λ, or 10λ and an upper limit of any of 100λ, 80λ, 60λ, or 40λ, wherein λ is a wavelength corresponding to a central frequency in the first range of frequencies.

The diameter of the core may be in a range have a lower limit of any of 5 microns, 7 microns, 10 microns, and 12 microns and an upper limit of any of 170 microns, 120 microns, and 100 microns, and 50 microns.

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The first range of frequencies may correspond to wavelengths in the range of about 1.2 microns to 1.7 microns. Alternatively, the first range of frequencies may correspond to wavelengths in the range of about 0.7 microns to 0.9 microns. The ratio of the bandwidth of the first range of frequencies and the central frequency and may be at least about 10%.

The waveguide axis may be substantially straight or it may include one or more bends. The core may have a circular cross-section, a hexagonal cross-section, or a rectangular cross-section.

The confinement region may guide at least one mode to propagate along the waveguide axis with radiative losses less than 0.1 dB/km, or even less than 0.01 dB/km for a frequency in the first range of frequencies. For example, the mode may be a TE mode (e.g., TE_{01}). The waveguide may support a mode in which at least 99% of the average energy of the propagating EM radiation is in the core for a frequency in the first range of frequencies.

The confinement region may include at least two dielectric materials having different refractive indices. The ratio of the refractive index of the higher index dielectric material to that of the lower index dielectric material may be greater than 1.1, greater than 1.5, or greater than 2. For example, the lower-index dielectric material may include a polymer or a glass, and the higher-index dielectric material may include germanium, tellurium, or a chalcogenide glass.

The photonic bandgap may be an omnidirectional photonic bandgap. The photonic bandgap may be sufficient to cause EM radiation that is incident on the confinement region from the core in the first frequency range and with any polarization to have a reflectivity for a planar geometry that is greater than 95% for angles of incidence ranging from 0° to at least 80°. The photonic crystal may be a a one-dimensional photonic crystal or a two-dimensional photonic crystal.

The confinement region may include alternating layers of the two dielectric material surrounding the core about the waveguide axis. For example, the refractive indices and thicknesses of at least some of the alternating dielectric layers substantially satisfy the following equality: $\dfrac{d_{hi}}{d_{lo}} = \dfrac{\sqrt{n_{lo}^2 - 1}}{\sqrt{n_{hi}^2 - 1}}$, where d_{hi} and d_{lo} are the thicknesses of adjacent higher-index and lower-index layers, respectively, and n_{hi} and n_{lo} are the refractive indices of the adjacent higher-index and lower-index layers, respectively. The confinement region may

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include at least 12 pairs of the alternating layers. The waveguide may support at least one mode propagating along the waveguide axis for which the confinement region includes a sufficient number of pairs of alternating layers to limit radiative losses of the mode to less than 0.1 dB/km or even less than 0.01 dB/km for a frequency in the first range of frequencies.

5   At least a first end of the waveguide may include a coupling segment over which the refractive index cross-section is continuously varied to alter the field profile of the working mode. Furthermore, there may be a second waveguide coupled to the first mentioned waveguide, wherein the cross-section of the second waveguide adjacent the first waveguide includes regions of doped silicon located to improve coupling of the working mode into the

10   second waveguide. Alternatively, or in addition, the cross-section of the second waveguide adjacent the first waveguide may include a hollow ring contacting the dispersion tailoring region of the first waveguide to thereby improve coupling of the working mode into the second waveguide.

            In another aspect, the invention features an optical telecommunications system

15   including: (i) a transmitter generating an optical signal; and (ii) any of the optical waveguides described above coupled at one end to the transmitter to carry the optical signal, wherein the optical signal is at a frequency in the first frequency range. The optical waveguide may have a length greater than 30 km, greater than 200 km, or greater than 500 km.

            The system may further include an optical receiver coupled to the other end of the

20   optical waveguide to detect the optical signal, an optical amplifier coupled to the other end of the optical waveguide to amplify the optical signal, an optical regenerator coupled to the other end of the optical waveguide to regenerate the optical signal as an electrical signal, and/or a dispersion compensation module coupled to the other end of the optical waveguide to introduce dispersion to the optical signal that substantially cancels dispersion caused by

25   the optical waveguide. The optical signal may be at a wavelength in the range of about 1.2 microns to about 1.7 microns or in the range of about 0.7 microns to about 0.9 microns. Furthermore, the transmitter may generate multiple signals at different wavelengths, and wherein the different wavelengths correspond to frequencies in the first frequency range.

            In general, in another aspect, the invention features a method of designing a photonic

30   crystal optical waveguide including a dielectric core region extending along a waveguide axis and a dielectric confinement region surrounding the core about the waveguide axis, wherein

the confinement region is configured to guide EM radiation in at least a first range of frequencies to propagate along the waveguide axis and wherein the core has an average refractive index smaller than about 1.3 for a frequency in the first range of frequencies. The method includes selecting a diameter for the core based on one or more design criteria for the guided EM radiation including mode separation, group-velocity dispersion, radiative losses, absorption losses, and cladding nonlinearity suppression. For example, the diameter for the core may be based on at least two of the design criteria. In particular, an upper limit for the diameter of the core may be selected based on the mode separation, and a lower limit for the diameter may be selected based on at least one of the group-velocity dispersion, the radiative losses, the absorption losses, and the cladding nonlinearity suppression. Furthermore, the confinement region may include at least two dielectric materials having different refractive, and the method may further include selecting an index contrast for the different refractive indices based on at least one of the design criteria including the radiative losses, the absorption losses, and the cladding nonlinearity suppression.

Unless otherwise defined, all technical and scientific terms used herein have the same meaning as commonly understood by one of ordinary skill in the art to which this invention belongs. Although methods and materials similar or equivalent to those described herein can be used in the practice or testing of the present invention, suitable methods and materials are described below. All publications, patent applications, patents, and other references mentioned herein are incorporated by reference in their entirety. In case of conflict, the present specification, including definitions, will control. In addition, the materials, methods, and examples are illustrative only and not intended to be limiting.

Additional features, objects, and advantages of the invention will be apparent from the following detailed description and drawings, and from the claims.

DESCRIPTION OF DRAWINGS

The invention will now be further described merely by way of example with reference to the accompanying drawings in which:

Figure 1 is a schematic diagram of the cross-section of a photonic crystal waveguide fiber 100.

Figure 2 are schematic diagrams of the cross-sections of a Bragg fiber waveguide (left panel) and a hollow metallic waveguide (right panel).

Figure 3 are photonic band diagrams for a planar Bragg mirror (left panel) and a hollow metallic waveguide (right panel).

5   Figure 4 is a photonic band diagram graph of a Bragg fiber.

Figure 5 are plots of the TE_{01} (left panel) and EH_{11} (right panel) field distributions.

Figure 6 is a graph of radiation leakage for modes of a large core (R=30a), 17-layer hollow Bragg fiber.

Figure 7 is a graph of group velocity (chromatic) dispersion for the TE_{01} mode of the

10   large core Bragg fiber.

Figure 8 is a graph of absorption losses from the cladding material for modes of the large core Bragg fiber.

Figure 9 is a graph of the cladding nonlinearity suppression for the TE_{01} mode of the large core Bragg fiber.

15   Figure 10 is a graph showing the scaling properties of absorption and nonlinearities with respect to core radius in a Bragg fiber.

Figure 11 is a schematic diagram of an optical telecommunication system that implements large core photonic crystal waveguide fibers described herein.

DETAILED DESCRIPTION

20   The invention features a photonic crystal fiber waveguide 100 having small attenuation rates, exhibiting small nonlinearities, and providing effectively single-mode operation.

Basic Structure

25   The cross-section of waveguide 100 is shown in Figure 1 and includes a dielectric core 110 extending along a waveguide axis and a dielectric confinement region 120 surrounding the core. In the embodiment of Figure 1, confinement region 120 is shown to include alternating layers 122 and 124 of dielectric materials having different refractive indices. One set of layers, e.g., layers 122, define a high-index set of layers having an index

30   n_{hi} and a thickness d_{hi}, and the other set of layers, e.g., layers 124, define a low-index set of

layers having an index n_{lo} and a thickness d_{lo}, where $n_{hi} > n_{lo}$. For convenience only a few of the dielectric confinement layers are shown in Figure 1. In practice, confinement region 120 may include many more layers (e.g., twenty or more layers). Waveguide 100 may further include an additional structural cladding layer 140 surrounding the confinement region 120 to

5   provide structural support to the waveguide as a whole. Because structual layer 140 does not contribute substantially to the optical properties (e.g., radiative losses and dispersion) of the waveguide, we do not discuss it further.

To simplify numerical calculations in the sections that follow, we assume a circular cross-section for fiber waveguide 100, with core 110 having a circular cross-section and

10   region 120 (and layers therein) having an annular cross-section. In other embodiments, however, the waveguide and its constituent regions may have different geometric cross-section such as a rectangular or a hexagonal cross-section. Furthermore, as mentioned below, core and confinement regions 110 and 120 may comprise multiple dielectric materials having different refractive indices. In such cases, we may refer to an "average refractive

15   index" of a given region, which refers to the sum of the weighted indices for the constituents of the region, where each index is weighted by the fractional area in the region of its constituent. The boundary between region 110 and 120, however, is defined by a change in index. The change may be caused by the interface of two different dielectric materials or by different dopant concentrations in the same dielectric material (e.g., different dopant

20   concentrations in silica).

Dielectric confinement region 120 guides EM radiation in a first range of frequencies to propagate in dielectric core 110 along the waveguide axis. The confinement mechanism is based on a photonic crystal structure in region 120 that forms a bandgap including the first range of frequencies. Because the confinement mechanism is not index-guiding, it is not

25   necessary for the core to have a higher index than that of the portion of the confinement region immediately adjacent the core. To the contrary, core 110 may have a lower average index than that of confinement region 120. For example, core 110 may be air or vacuum. In such a case, EM radiation guided in the core will have much smaller losses and much smaller nonlinear interactions than EM radiation guided in a silica core, reflecting the smaller

30   absorption and nonlinear interaction constants of many gases relative to silica or other such solid material. In additional embodiments, for example, core 110 may include a porous

dielectric material to provide some structural support for the surrounding confinement region while still defining a core that is largely air. Accordingly, core 110 need not have a uniform index profile.

5   The alternating layers 122 and 124 of confinement region 120 form what is known as a Bragg fiber. The alternating layers are analogous to the alternating layers of a planar dielectric stack reflector (which is also known as a Bragg mirror). The annular layers of confinement region 120 and the alternating planar layers of a dielectric stack reflector are both examples of a photonic crystal structure. Photonic crystal structures are described generally in <u>Photonic Crystals</u> by John D. Joannopoulos et al. (Princeton University Press,

10   Princeton NJ, 1995).

As used herein, a photonic crystal is a dielectric structure with a refractive index modulation that produces a photonic bandgap in the photonic crystal. A photonic bandgap, as used herein, is a range of frequencies in which there are no accessible extended (i.e., propagating, non-localized) states in the dielectric structure. Typically the structure is a

15   periodic dielectric structure, but it may also include, e.g., more complex "quasi-crystals." The bandgap can be used to confine, guide, and/or localize light by combining the photonic crystal with "defect" regions that deviate from the bandgap structure. Moreover, there are accessible extended states for frequencies both below and above the gap, allowing light to be confined even in lower-index regions (in contrast to index-guided TIR structures). The term

20   "accessible" states means those states with which coupling is not already forbidden by some symmetry or conservation law of the system. For example, in two-dimensional systems, polarization is conserved, so only states of a similar polarization need to be excluded from the bandgap. In a waveguide with uniform cross-section (such as a typical fiber), the wavevector β is conserved, so only states with a given β need to excluded from the bandgap

25   to support photonic crystal guided modes. Moreover, in a waveguide with cylindrical symmetry, the "angular momentum" index m is conserved, so only modes with the same m need to be excluded from the bandgap. In short, for high-symmetry systems the requirements for photonic bandgaps are considerably relaxed compared to "complete" bandgaps in which all states, regardless of symmetry, are excluded.

30   Accordingly, the dielectric stack reflector is highly reflective in the photonic bandgap because EM radiation cannot propagate through the stack. Similarly, the annular layers in

confinement region 220 provide confinement because they are highly reflective for incident rays in the bandgap. Strictly speaking, a photonic crystal is only completely reflective in the bandgap when the index modulation in the photonic crystal has an infinite extent. Otherwise, incident radiation can "tunnel" through the photonic crystal via an evanescent mode that

5 couples propagating modes on either side of the photonic crystal. In practice, however, the rate of such tunneling decreases exponentially with photonic crystal thickness (e.g., the number of alternating layers). It also decreases with the magnitude of the index contrast in the confinement region.

Furthermore, a photonic bandgap may extend over only a relatively small region of

10 propagation vectors. For example, a dielectric stack may be highly reflective for a normally incident ray and yet only partially reflective for an obliquely incident ray. A "complete photonic bandgap" is a bandgap that extends over all possible wavevectors and all polarizations. Generally, a complete photonic bandgap is only associated with a photonic crystal having index modulations along three dimensions. However, in the context of EM

15 radiation incident on a photonic crystal from an adjacent dielectric material, we can also define an "omnidirectional photonic bandgap," which is a photonic bandgap for all possible wavevectors and polarizations for which the adjacent dielectric material supports propagating EM modes. Equivalently, an omnidirectional photonic bandgap can be defined as a photonic band gap for all EM modes above the light line, wherein the light line defines the lowest

20 frequency propagating mode supported by the material adjacent the photonic crystal. For example, in air the light line is approximately given by $\omega = c\beta$, where ω is the angular frequency of the radiation, β is the wavevector, and c is the speed of light. A description of an omnidirectional planar reflector is disclosed in U.S. Patent 6,130,780, the contents of which are incorporated herein by reference. Furthermore, the use of alternating dielectric

25 layers to provide omnidirectional reflection (in a planar limit) for a cylindrical waveguide geometry is disclosed in Published PCT application WO 00/22466, the contents of which are incorporated herein by reference.

When alternating layers 122 and 124 in confinement region 120 give rise to an omnidirectional bandgap with respect to core 110, the guided modes are strongly confined

30 because, in principle, any EM radiation incident on the confinement region from the core is completely reflected. However, such complete reflection only occurs when there are an

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infinite number of layers. For a finite number of layers (e.g., about 20 layers), an omnidirectional photonic bandgap may correspond to a reflectivity in a planar geometry of at least 95 % for all angles of incidence ranging from 0° to 80° and for all polarizations of EM radiation having frequency in the omnidirectional bandgap. Furthermore, even when

5   waveguide 100 has a confinement region with a bandgap that is not omnidirectional, it may still support a strongly guided mode, e.g., a mode with radiation losses of less than 0.1 dB/km for a range of frequencies in the bandgap. Generally, whether or not the bandgap is omnidirectional will depend on the size of the bandgap produced by the alternating layer (which generally scales with index contrast of the two layers) and the lowest-index

10   constituent of the photonic crystal.

In additional embodiments, the dielectric confinement region may include photonic crystal structures different from a multilayer Bragg configuration. For example, rather than the Bragg configuration, which is an example of a one-dimensionally periodic photonic crystal (in the planar limit), the confinement region may be selected to form, for example, a

15   two-dimensionally periodic photonic crystal (in the planar limit), such as an index modulation corresponding to a honeycomb structure. See, for example, R.F. Cregan et al., *Science* 285:1537-1539, 1999. Furthermore, even in a Bragg-like configuration, the high-index layers may vary in index and thickness, and/or the low-index layers may vary in index and thickness. In general, the confinement region may be based on any index modulation

20   that creates a photonic bandgap.

The multilayer waveguides may be fabricated using multilayer co-drawing techniques, co-extrusion techniques, or deposition techniques. Suitable high-index materials may include chalcogenide glasses such as binary and ternary glass systems, heavy metal oxide glasses, amorphous alloys, and high-index doped polymers. Suitable low-index

25   materials may include oxide glasses such as borosilicate glasses, halide glasses, and poymers such as polystyrene. In addition, low-index regions may be fabricated by using hollow structural support materials, such as silica spheres or hollow fibers, to separate high-index layers or regions.

In general, computational methods known in the art can be used to determine the

30   modal properties of the dielectric waveguides described herein. Furthermore, iterative calculations may be used to determine waveguide specifications that optimize selected

waveguide properties. We outline below some of the basic physics that underlie such calculations. In particular, the EM modes supported by a structure can be solved numerically according to Maxwell's equations and the boundary conditions for the structure. Furthermore, for an all-dielectric, isotropic structure, Maxwell's equations can be reduced to:

$$\nabla \times \left(\frac{1}{\varepsilon(\mathbf{r})} \nabla \times \mathbf{H}(\mathbf{r}) \right) = \left(\frac{\omega^2}{c^2} \right) \mathbf{H}(\mathbf{r}) \tag{1}$$

$$\nabla \cdot \mathbf{H}(\mathbf{r}) = \nabla \cdot \mathbf{E}(\mathbf{r}) = 0 \tag{2}$$

$$\mathbf{E}(\mathbf{r}) = \left(\frac{-ic}{\omega \varepsilon(\mathbf{r})} \right) \nabla \times \mathbf{H}(\mathbf{r}) \tag{3},$$

where $\mathbf{H}$ and $\mathbf{E}$ are the macroscopic magnetic and electric fields, respectively, and ε is the scalar dielectric constant for the structure. To solve for the EM modes of such a structure, one solves the eigenvalue equation given by Eq. 1 (where $\mathbf{H}$ is the eigenfunction and ω^2/c^2 is the eigenvalue) subject to the divergence equation, Eq. 2, to give $\mathbf{H}$. Thereafter, one can determine $\mathbf{E}$ from $\mathbf{H}$ according to Eq. 3.

Often symmetry can be used to simplify the solution. For example, with respect to many of the particular example described herein, we may assume continuous translational symmetry (i.e., a uniform cross-section) along its longitudinal axis, which we shall denote as the z-axis. Of course, in practice the structures may have small deviations from such uniformity. Moreover, the structures will have a finite spatial extent. Nonetheless, based on the assumption of a uniform cross-section for some length that is large relative to the waveguide diameter, the EM modes supported by the waveguides can be written schematically as $F(x,y,z) = \exp[i(\beta z - \omega t)]F(x,y)$, where F is any of the electromagnetic field components. The parameter β in the expression for F is the longitudinal wavevector.

In the following sections we provide a more detailed analysis of photonic crystal fiber waveguide 100 and the parameters that lead to optimal performance for long distance optical telecommunications. The analyses focus on a Bragg fiber arrangement, but the results and scaling laws may be extended to large core photonic crystal fibers in general.

Hollow Dielectric vs. Metallic Waveguides

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Insight into the principles of dielectric waveguide 100 may be achieved through analogy with a hollow metallic waveguides. Figure 2 shows a hollow dielectric photonic crystal waveguide 200 having core radius R (left panel) contrasted with a hollow metallic waveguide 210 having a core radius R (right panel). In dielectric waveguide 200, the hollow

5   core (index of refraction unity) is surrounded by a multilayer confinement region (hereinafter "cladding") that includes of alternating layers having high (dark) and low (light) indices of refraction. In the presently described embodiment, the indices of refraction of the cladding layers are selected to be 4.6 and 1.6 and have thicknesses of 0.33a and 0.67a, respectively, where a is the thickness of one high/low bilayer. Once a mode frequency v is computed

10   units of c/a, where c is the speed of light, the physical value of a is determined via $a=\lambda\backslash v$ for some desired operational wavelength λ. The radius R of the waveguide will vary in the differing examples presented herein, for example, from a minimum of $2a$ to a maximum of $100a$. As we shall see, values of R greater than about $5a$ (or even greater than $10a$ or $20a$) have many advantages.

15   Metallic waveguide 210 has as that of hollow dielectric waveguide 200, but a metal cylinder replaces the multilayer dielectric cladding. In the metallic case, light is confined in the core by the impenetrability of a near-perfect metal (something that is practical nonexistent at optical frequencies). The confined modes for metallic waveguide 210 with $R=2a$ are depicted in Figure 3 (right panel) for the lowest seven modes. The dispersion

20   relations shown in Figure 3 depict two conserved quantities: the axial wavenumber β and the frequency ω. By symmetry, modes of a cylindrical waveguide can also be labeled by their "angular momentum" integer m. For waveguides that lie along the z axis, the (z, t, φ) dependence of the modes is then given by: $exp[i(\beta z - \omega t + m\varphi)]$, where φ is the azimuth coordinate for the cylinder. In the hollow metal tube, the eigenmodes are purely polarized as

25   TM ($H_z=0$) or TE ($E_z=0$), and the l-th mode of a given m is labeled TX_{ml}.

In the dielectric case, light is confined by the one-dimensional photonic band gap of the multi-layer cladding, which is easy to analyze in the limit as the cladding becomes planar. The resulting band structure is shown in the left panel of Figure 3. The dark regions in the left panel of Figure 3 correspond to (β,ω) pairs for which light can propagate in the within the mirror, whereas the white and gray regions correspond to situations where light cannot

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propagate in the mirror. The thick black line in the left panel of Figure 3 corresponds to the light line ($\omega=c\beta$) and the gray regions correspond to frequency regions of omnidirectional reflectivity for the mirror. For the planar dielectric mirror, β is the surface-parallel wavevector component. In the photonic gap regions (the white and gray regions), we expect

5   the mirrors to behave similarly to a metal, and confine modes strongly. Because every eigenmode has a finite, conserved m, the effective wavevector $k_\varphi=m/r$ in the φ direction goes to zero as r becomes large. If this were not true, there could be no band gaps in Figure 3 because non-zero $k_\varphi \perp \beta$ would have to be projected on the Bragg band diagram. Notably, the Bragg band diagram shows ranges of omnidirectional reflection (gray regions), which

10   correspond to frequencies at which any incident wave from air are reflected by the planar mirrors (and vice versa). Omnidirectional reflection per se is not strictly necessary for guidance in these fibers, but its presence is strongly correlated with the regimes of large, polarization-independent gaps along the light line.

      Bragg mirrors have different band-gaps for "TE" and "TM" polarizations, referring to

15   fields purely parallel to the interface and fields with a normal component, respectively. (Both polarizations are shown in Figure 3. Strictly speaking, this corresponds to the metallic waveguide TE and TM labels only for $m=0$; all non-zero m modes have some nonzero E_r component.

      The modes supported by any cylindrical waveguide, including metallic waveguides,

20   Bragg fibers, and conventional index-guided fibers, can be computed by a transfer-matrix method in which the longitudinal fields ($E\{z\}$ and $H\{z\}$) of a given (m, ω, β) in an annular region of index n_j are expanded in Bessel functions $J_m(k_j r)$ and $Y_m(k_j r)$, with $k_j \equiv \sqrt{n_j^2 \omega^2 / c^2 - \beta^2}$. At each interface, the coefficients are related by a 4x4 transfer matrix that matches boundary conditions. The product of all these transfer matrices yields a single

25   matrix relating the fields in the core to those in the outermost cladding. Then, by application of appropriate boundary conditions, the β_n wavevectors of the various modes can be found, as discussed further below.

      For the moment, we are primarily interested in the modes that lie within the band gap of the one-dimensional Bragg mirrors. Such modes must decay exponentially with r in the

30   cladding (i.e., confinement region), and therefore are truly guided modes in the limit of

infinitely many cladding layers (the case of finite layers is considered further below). Most of these modes lie above the $\omega = c\beta$ light line, and thus propagate within the hollow core in much the same way as the modes of a metallic waveguide. It is also possible, however, for modes to lie beneath the light line and yet inside the band gap, in which case they are surface states

5 localized around the core/cladding interface.

In Figure 4, we show the first couple guided modes computed for a Bragg fiber with core-radius $R=2a$ and the above-mentioned planar-mirror parameters. The light-colored lines in Figure 4 are for TE and HE modes, while the dark-colored lines are for TM and EH modes, and again the thick black line is the light line ($\omega = c\beta$). The dark solid regions in

10 Figure 4 represent the continuum of modes that propagate within the multilayer cladding. The guided modes are at nearly the same frequencies as those for the guided modes of the metallic waveguide in Figure 3 (right-panel), with the one-dimensional bandgaps superimposed. In the dielectric waveguide, the modes are only purely TE and TM for m=0, but for non-zero m they are strongly TE-like or TM-like, and are called HE and EH,

15 respectively. Furthermore, when a mode enters the second gap, we add a prime superscript. We also find that the guided modes in the Bragg fiber have the same orthogonality relationships as those of the metallic waveguide and conclude that their respective field patterns must also be nearly identical.

20 **Large Core Bragg Fibers**

The above calculations yielded the modes of a Bragg fiber for a radius R=2a. This small radius has the advantage of supporting only a few modes, which are easy to plot and understand in their entirety and even has a single-mode frequency range. The analogy with metallic waveguides, however, indicates that this may not be the most desirable regime for

25 fiber operation.

In metallic waveguides, the lowest-loss mode is TE_{01}, and its ohmic losses decrease as $1/R^3$. Moreover, the differential losses between TE_{01} and other modes create a modal-filtering effect that allows these metallic waveguides to operate in an effectively single-mode fashion. On the other hand, for large core radii (high frequencies), losses become dominated

30 by scattering into other closely-spaced modes, especially into the degenerate TM_{11} mode via bends.

Similar results hold for OmniGuide fibers: the lowest-loss mode is TE_{01} and many of its losses fall off as $1/R^3$. Like the metallic waveguides, and unlike conventional index-guided optical fibers with their small material contrasts, we demonstrate a strong modal-filtering effect based on the degree of confinement in the core. Also as before, inter-modal

5   scattering worsens with increasing R.

Based on such considerations, and as demonstrated further below, we find that a core radius in the range of about *5a* to 100*a* (or even *7a* to about *70a, or* even 10*a* to about *50a*) leads to desirable results. For a central wavelength λ in the middle of the frequencies guided by the waveguide, these range may be approximately expresses as *2λ<R<40λ*, with similar

10   sub-ranges.

In the next couple sections, we focus on an embodiment of a Bragg fiber having a hollow core radius of $R=30a$, and a confinement region having 17 layers. The 17 layers start with a high-index layer of index 4.6 and alternate with a low-index layer of index 1.6. The thicknesses of the high-index and low-index layers are 0.22a and 0.78a, respectively. The

15   point of lowest TE_{01} dissipation losses (which is discussed further below) then lies at a frequency of $\omega \cong 0.28 \cdot 2\pi c/a$, so if we make this correspond to the standard $\lambda=1.55$ microns of telecommunications, we have $a=0.434$ microns. Equivalently, $R=13.02=8.4\lambda$.

In order to choose the layer thicknesses of the confinement layers, we employ an approximate quarter-wave condition. It is well-known that, for normal incidence, a maximum

20   band gap is obtained for a "quarter-wave" stack in which each layer has equal optical thickness $\lambda/4$, or equivalently $d_{hi} / d_{lo} = n_{lo} / n_{hi}$, where d and n refer to the thickness and index, respectively, of the high-index and low-index layers. Normal incidence, however, corresponds to $\beta=0$, whereas for a cylindrical waveguide the desired modes typically lie near the light line $\omega=c\beta$ (in the limit of large R, the lowest-order modes are essentially plane

25   waves propagating along z-axis, i.e., the waveguide axis). In this case, the quarter-wave condition becomes:

$$\frac{d_{hi}}{d_{lo}} = \frac{\sqrt{n_{lo}^2 - 1}}{\sqrt{n_{hi}^2 - 1}} \qquad (4)$$

Strictly speaking, Equation (4) may not be exactly optimal because the quarter-wave condition is modified by the cylindrical geometry, which may require the optical thickness of each layer to vary smoothly with its radial coordinate. Nonetheless, we find that Eq. (4) provides an excellent guideline for optimizing many desirable properties, especially for core radii larger than the mid-gap wavelength.

As in the R=2a case, the guided-modes of this $R=30a$ Bragg fiber can be labeled by analogy to the modes of an equal-radius metallic waveguide. Tranverse electric field profiles of two such modes in the Bragg fiber, the lowest-loss TE_{01} and the linearly-polarized EH_{11} (analogous mode to the TM_{11} in a metallic guide) are depicted in Figure 5 for $\omega=0.28(2\pi c/a)$ (which corresponds to $\beta=0.27926(2\pi c/a)$ and $\beta=0.27955(2\pi c/a)$ for the two modes, respectively). The TE_{01} mode is circularly symmetric and "azimuthally" polarized $\left(\vec{E} \perp \hat{\varphi}\right)$. Thus, unlike the doubly-degenerate EH_{11} mode (two orthogonal polarizations), cannot be split into two modes of differing velocities by fiber imperfections, and is therefore immune to polarization-mode dispersion (PMD). We note that the mode labeling in a Bragg fiber is more complex than in a metallic waveguide, because sometimes a mode will cross the light line and become a surface state localized around the core/cladding interface. When that happens, another mode moves "up" and takes its place; for example, the TM_{01} mode crosses the light line at $\omega=0.27(2\pi c/a)$, while the TM_{02} mode continuously takes on the core field pattern of TM_{01}. When in doubt, we label a mode as HE or EH depending upon whether it is dominated by H_z or E_z at $r=0$, respectively, and number the core modes according to their ordering above the light line.

Scaling Laws with Core Size

Because of the strong reflectivity of the dielectric confinement mirrors, many of the mode properties are determined largely by the geometric size R of the core, within which the modes are confined. Subsequently we derive scaling relations for the different quantities computed, and in this section we lay the groundwork for those derivations by presenting basic scalings of the fields and modes. These scaling relations are largely independent of details such as the precise index contrast that is used, so long as it is sufficiently large for the metallic analogy to hold, and will provide a broad understanding of the advantages and tradeoffs of a Bragg fiber structure.

In particular, we will focus on the suppression of cladding phenomena for the TE_{0l} (especially TE_{01}) modes of the fiber. A critical property of TE_{0l} modes is that, by analogy with a hollow metallic waveguide, they have a node in their electric field near r=R. It then follows that the amplitude of the electric field in the cladding is proportional to the slope of E_φ at R. The form of E_φ in the core, however, is simply the Bessel function $J_1(\xi r/R)$, where $\xi(\omega)$ is roughly the l-th zero of J_1. The slope at R is then $(J_0(\xi)- J_2(\xi))(\xi/2R)$. Moreover, for the quarter-wave stack, the value of E_φ is maximized at near each of the high-index layer to low-index layer interfaces. Thus, not including any normalization of the J_1 amplitude (i.e., $E_\varphi \sim 1$), we find that the unnormalized E_φ in the cladding scales as d_{hi}/R. In addition, typically we must normalize the power of the field: this means dividing the electric field vector E by an additional factor proportional to the square root of the mode area, which is proportional to R, and so:

$$\text{normalized } TE_{01} \text{ cladding } \vec{E} \propto \frac{1}{R^2} \qquad (5)$$

Moreover, the area of the field in the cladding is the perimeter (which scales as R) times some constant (penetration depth) that depends on the size of the of the band gap. Combining this with Eq. 5 gives:

$$\text{fraction of } \int |\vec{E}^2| \text{ in cladding for } TE_{01} \propto \frac{1}{R^3} \qquad (6)$$

and from this we derive many other scaling relations. In contrast, for TM or mixed-polarization modes with an E_r component, the unnormalized field amplitude in the cladding remains roughly constant with changing R, thus their fractional energy density in the cladding then scales as only $1/R$, so the cladding has a much greater effect on them.

By general phase-space arguments, the total number of modes in the core must scale as the area R^2. Moreover, in a metal waveguide, the dispersion relations look like $\beta_n = \sqrt{\omega^2/c^2 - \xi_n^2/R^2}$, where ξ_n are roots or extrema of Bessel functions. Therefore, far from cutoff $(R>>\xi_n c/\omega)$, we have:

$$\text{mode separation } \Delta\beta \propto \frac{1}{R^2} \qquad (7)$$

Unfortunately, $\Delta\beta$ can be somewhat more complicated in a Bragg fiber, due to the finite field penetration into the cladding and due to the transitions into surface states and subsequent mode relabelings discussed earlier. For example, consider the case of the EH_{11} mode, which is degenerate with TE_{01} in the metallic limit. In the Bragg fiber, however, the degeneracy is broken by the penetration of the fields into the cladding. Such degeneracy breaking can also be understood in terms of the phase shift of a TE/TM polarized wave upon reflection from the dielectric multilayer mirror, which induces a small shift $\Delta\beta$: by perturbation theory, $\Delta\beta$ is proportional to the amount of EH_{11} energy in the cladding, which scales inversely with R:

$$\text{TE}_{01} \text{ and EH}_{11} \text{ mode separation } \Delta\beta \propto \frac{1}{R} \tag{8}$$

Testing this scaling relation numerically for $\lambda=1.55$ microns, however, we find that this separation eventually scales as $1/R^2$ for R greater than or equal to about 40a . It turns out that the "fundamental" HE_{11} mode has crossed the light line to become a surface state, and EH_{11} continuously transitions to being more HE_{11}-like, thus scaling eventually as Eq. 7.

Leaky Modes and Radiation Loss

In the preceding discussion, we have neglected a point that may seem important: in reality, there will be only a finite number of cladding layers in the confinement region. Because of this, and the fact that the modes of interest lie above the light line of the outermost region, the field power will slowly leak out in a process akin to quantum-mechanical "tunneling." This radiation loss, however, decreases exponentially with the number of cladding layers, and we quantify its smallness explicitly below. We find that only a small number of layers is required to achieve leakage rates well below 0.1 dB/km. Moreover, the radiation leakage strongly differs between modes, inducing a modal-filtering effect that allows a large-core Bragg fiber to operate in an effectively single-mode fashion.

In the limit of infinitely many cladding layers, the modes in the OmniGuide core are true confined modes, thanks to the band gap, with discrete real eigenvalues β_n. For finitely many layers, modes are no longer truly confined (above the outermost light line), leading to a continuum of β values with infinitely-extended eigenstates. The former confined modes become leaky resonances: superpositions of real-β eigenmodes centered on β_n with a width $\Delta\beta$ proportional to the radiative decay rate α_n. Such resonances can be studied directly via

the physical real-β continuum, but a powerful alternative method is the leaky-mode technique, which employs a conceptual analytic continuation from a real β to $\tilde{\beta}$ in the complex plane to satisfy a boundary condition of zero incoming flux. The power decay rate α_n is then given by $2Im\{\tilde{\beta}_n\}$, where Im denotes the imaginary part.

5   For the Bragg fiber, the leaky-mode method is as follows. The transfer-matrix formulation allows one to compute 2x2 matrices $M_m^{\pm}(\omega,\beta)$ that connect the TE and TM amplitudes at the origin to the amplitudes of the outgoing (+) or incoming (-) TE and TM cylindrical waves (Hankel functions) in the outermost region, as a function of ω and β for a given angular-momentum index m. For a leaky mode, we wish to impose the boundary

10   condition of zero incoming waves, so that there are no sources at infinity; such a solution exists whenever there is a zero eigenvalue of M_m^-. Therefore, we use the determinant:

$$f_m\left(\omega,\tilde{\beta}\right) \equiv \det\left[M_m^-\left(\omega,\tilde{\beta}\right)\right] \tag{9}$$

15   so that the leaky mode is defined by $f_m\left(\omega,\tilde{\beta}_n\right) = 0$. Once $\tilde{\beta}_n$ is found for a given ω, the corresponding eigenvector of $M_m^-\left(\omega,\tilde{\beta}_n\right)$ yields the required mixed-polarization amplitudes. With finitely many layers, the only real roots of f_m lie below the light line of the outermost region. (We note that below the light line of the outermost region, the incoming-wave Hankel function instead becomes an exponentially-growing function, but its coefficient must

20   be zero all the same.) Above this light line, the incoming and outgoing flux are equal for real β, corresponding to steady-state standing-wave patterns. The small imaginary part of $\tilde{\beta}_n$ above the light line yields the power decay rate $\alpha_n=2Im\{\tilde{\beta}_n\}$.

For all modes, the radiative decay α_n decreases exponentially with increasing numbers of cladding layers, thanks to the exponential decay of fields in the Bragg band gap,

25   eventually to the point where other losses (e.g. absorption) dominate. At λ=1.55 microns for this structure, the TE losses decrease by a factor of about 10 per cladding bilayer and the TM losses decrease by a factor of 5 per cladding bilayer. Because of the smaller TM band gap, the losses of mixed-polarization (non-zero m) modes are eventually dominated by their less-

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confined TM components. In Figure 6, we display the computed radiation leakage rates α_n for the 17-layer, $R=30a$ structure parametrized earlier corresponding to the lowest-loss TE_{01} mode, the next-lowest loss TE_{02} mode, and the linearly-polarized EH_{11} mode to typify mixed-polarization modes. Like the absorption discussed later, these differential losses create a mode-filtering effect that allows the TE_{01} mode to operate as effectively single-mode, even for large-core Bragg fibers. From Figure 6, it is seen that with only 17 cladding layers the TE_{01} mode has leakage rates well under 0.01 dB/km, and even EH_{11} has decay lengths of meters. Thanks to these low losses, the modes can be treated as truly bound for most analyses (e.g. dispersion relations and perturbation theory), with the leakage rates at most included as an independent loss term.

The radiation losses are proportional to the field amplitude $\left|\vec{E}\right|^2$ in the cladding, which goes like $1/R^4$ for TE_{01} from Eq. 5, multiplied by the surface area (which scales as R). Thus:

$$TE_{01} \text{ radiation leakage } \alpha \propto \frac{1}{R^3} \tag{10},$$

which is the same as the scaling of TE_{01} ohmic losses in a hollow metallic waveguide. In contrast, because of their lack of a node near the boundary, TM and mixed-polarization radiation losses scale only as $1/R$.

Group-velocity Dispersion

Given a dispersion relation $\omega(\beta)$, one important quantity is the group-velocity dispersion D (the rate at which pulses spread), canonically defined as:

$$D \equiv -\frac{\omega^2}{2\pi c}\frac{d^2\beta}{d\omega^2} \tag{11}$$

in units of ps/(nm.km): the pulse-spreading (ps) per km of propagation per nm of $\Delta\lambda$. The dispersion D and the group velocity $v=d\omega/d\beta$ computed exactly from the function f of Eq. 9, which defines the dispersion relation implicitly by $f(\omega,\beta)=0$.

We can also consider material dispersion (non-zero variations in $n(\omega)$) introduced by the cladding, but we find that this has a negligible effect (due to the small field penetration into the cladding). For example, assuming that the cladding has the same material dispersion

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as silica at 1.55 microns, the contribution of material dispersion is less than 0.1 ps/(nm.km}
over most of the bandwidth. What remains is the waveguide dispersion, which stems from
the geometry of the core as well as the variable penetrability of the cladding. The resulting
dispersion as a function of wavelength is plotted in Figure 7 for the TE_{01} mode of the 17-layer

5   Bragg fiber (solid line) and a hollow metallic waveguide of the same radius (lighter line and
circles).

As we discuss in the next section, the practical implications of dispersion in a Bragg
fiber are quite different than in ordinary fibers, due to the absence of nonlinear effects.
Because dispersion no longer interacts with nonlinearities, it can in principle be completely

10   compensated after any distance of propagation, allowing one to put all dispersion
compensation at the end of a fiber link, as well as to tolerate higher dispersions. Conversely,
operating at or near a point of zero dispersion will no longer exacerbate four-wave mixing
noise.

Another important consideration is the relative dispersion slope (RDS), as measured

15   by (dD/dλ)/D; ideally this quantity is matched in any dispersion-compensation system. For
the 17-layer Bragg fiber above, the RDS is around 0.0007 nm^{-1}. This is 15 to 30 times
smaller than the RDS of contemporary TrueWave-RS^{TM} (0.010 nm^{-1}) and LEAF^{TM} (0.021
nm^{-1}) fibers, and smaller slopes are typically easier to achieve in dispersion-compensating
fibers.

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Suppression of Absorption and Nonlinearities

In this section, we compute the effect of absorption losses and nonlinearities in the
cladding materials of a Bragg fiber. We show that these effects are strongly suppressed for
the TE_{01} mode, allowing highly lossy and nonlinear materials to be employed, which greatly

25   broadens one's choices for high-index materials. Moreover, we will see that there is the
potential of greatly surpassing even the properties of silica fibers.

Absorption and nonlinearites correspond to tiny shifts in $\Delta\varepsilon$ in the dielectric constant
of the materials, and can therefore be treated by perturbation theory. This common technique
allows one to compute the shift $\Delta\beta$ due to a small perturbation, using only the unperturbed

30   modes (computed earlier via the transfer matrices). For absorption losses (also possibly
including Rayleigh scattering), $\Delta\varepsilon$ is a small imaginary part added to the dielectric constant ε

to represent the (material-dependent) dissipation rate. Using a first-order perturbation analysis, we calculate the losses of the TE_{01}, TE_{02}, and EH_{11} modes in our 17-layer Bragg fiber example by assuming that the core is lossless, and that both the high and low-index cladding layers have the same material dissipation rate α_0 (which may be expressed in

5   dB/m). Furthermore, we divide the computed dissipation rate α by α_0, yielding a dimensionless, material-loss independent absorption suppression coefficient of the respective mode. This was done for each frequency across the band gap, and the results are plotted in Figure 8. As one can see, the cladding losses are suppressed by more than four orders of magnitude over most of the bandwidth for the TE_{01}, a result that one may anticipate based on

10   the scaling law of Eq. 6. Furthemore, the losses for the TE_{01} are substantially smaller than those for the other modes, producing a mode-filtering effect that allows single-mode-like operation.

We now consider Kerr nonlinearities in the Bragg fiber. Such nonlinearities cause the index n of the material to vary as a function of electric-field strength: $n' \equiv n + n_2 \left|\vec{E}\right|^2$, where

15   n_2 is the "nonlinear index coefficient" of the material(s). To first order, the resulting perturbation to the dielectric constant can be expressed as: $\Delta\varepsilon = 2nn_2\left|\vec{E}\right|^2$.

Kerr nonlinearities cause several problems in fiber systems: self/cross-phase modulation (SPM/XPM), where the energy at one frequency shifts the β at the same/another frequency; and also four-wave mixing (FWM), in which energy at one frequency leaks into

20   another frequency. SPM and XPM interact with dispersion to limit dispersion-compensation schemes, and FWM causes noise/crosstalk between channels. Our concern here is not to compute these effects per se, but rather to define the limits in which they may be neglected.

The strength of nonlinearities in a fiber is given by a nonlinear lengthscale L_{NL}, defined as the inverse of the SPM phase shift $\Delta\beta$; this is the lengthscale at which SPM and

25   XPM become significant, and also appears as a scaling coefficient in the FWM noise. L_{NL} is inversely proportional to the mode power P (to first order), so we can also define a nonlinear strength $\gamma \equiv 1/PL_{NL} = \Delta\beta/P$, which is a power independent quantity proportional to the strength of nonlinear effects in the waveguide. We use first-order perturbation theory to calculate γ for the TE_{01} mode of our 17-layer Bragg fiber across the bandgap, assuming that

each cladding layer has the same value of n_2. We then divide those values γ by γ_0, which is the computed value for γ when we assume *both* the core and cladding have the n_2 nonlinearity. The resulting values provide a dimensionless nonlinearity suppression factor, which is plotted in Figure 10. The results show that the cladding nonlinearities are

5   suppressed by more than eight orders of magnitude over much of the bandwidth. Thus, the nonlinearities of the large core Bragg fiber will be dominated by the nonlinearities of air rather than those of the cladding, even for cladding materials thousands of times more nonlinear than silica. Because gases have Kerr constants almost 1000 times weaker than that of silica and the core area in our 17-layer fiber is almost 10 times larger than the effective

10   area of a typical silica fiber, our Bragg fiber has nonlinearities that are almost 10,000 times weaker than those of conventional silica fibers.

Such low nonlinearities would open dramatically new areas for fiber operation: for example, high powers, closely-spaced channels and/or low/zero dispersion without regard for FWM. In particular, FWM noise is proportional to $\gamma^2 / \left(\Delta\beta^2 + \alpha^2 \right)$, so even when the

15   channel spacing is made very small ($\Delta\beta$ approaching zero), small radiation/absorption losses α on the order 0.01 dB/km are still sufficient to minimize FWM when γ is small as it is here.

The results of Figures 8 and 9 follow directly from scaling laws as a function of core radius R. In particular, the first-order perturbation result involves an integrand proportional to the fraction of $\left| \vec{E} \right|^2$ in the cladding, which scales as $1/R^3$ as seen in Eq. 6, and thus we

20   have:

$$TE_{01} \ \ cladding \ \ absorption \propto \frac{1}{R^3} \qquad\qquad (12).$$

This is a familiar result, since it is the same as the scaling as that of ohmic dissipation

25   losses in a hollow metallic waveguide. The scaling for the nonlinear strength γ is found by similar arguments. Here, however, there is an additional factor of $\left| \vec{E} \right|^2$ from the nonlinear perturbation itself, which corresponds to a $1/R^4$ scaling from Eq. 5. As a result, the nonlinear

strength γ scales as $1/R^7$. On the other hand, the nonlinear strength γ_0 when one adds nonlinearities scales inversely with the area R^2 as in an ordinary optical fiber, so:

$$\text{TE}_{01} \text{ cladding nonlinearity } \quad \frac{\gamma}{\gamma_0} \propto \frac{1}{R^5} \tag{13}$$

5   It is because of these rapid $1/R^3$ and $1/R^5$ scalings that the cladding absorption and nonlinearities can be suppressed so strongly for the TE_{01} mode in a large-core Bragg fiber. To demonstrate these scaling laws explicitly, we plot the absorption and nonlinear suppression coefficients for the TE_{01} mode as a function of R in Figure 10, superimposing the predicted scaling laws. Hollow squares/circles show the computed values, and the solid lines display

10   the values predicted by starting from the 30a value and applying the scaling laws.

Scaling Laws with Index Contrast

    Although many of the previous computations assumed an index contrast of 4.6/1.6, the same qualitative results hold for a wide range of indices as long as the confinement

15   remains strong. The index contrast manifests itself in the decay rate of the field into the cladding, which determines the characteristic penetration depth d_p, and the analogy with the metallic waveguide remains valid when $d_p \ll R$. Below, we derive scaling relations to predict how Bragg fiber properties vary with the cladding indices (assuming $d_p \ll R$).

    In particular, with each bilayer of cladding, the fields decrease by some attenuation

20   factor $\kappa(\omega, \beta)$. For modes nearly on the light line, using "quarter-wave" bilayers according to Eq. 4, and defining $\tilde{n} = \sqrt{n^2 - 1}$, the mid-gap κ for TE/TM fields is:

$$\kappa_{te} \cong \frac{\tilde{n}_{lo}}{\tilde{n}_{hi}} \tag{14}$$

$$\kappa_{tm} \cong \frac{n_{lo}^2 \tilde{n}_{lo}}{n_{hi}^2 \tilde{n}_{hi}} > \kappa_{te} \tag{15}$$

25   The penetration depth d_p is then proportional to $a/(1-\kappa^2)$. Using the earlier scaling law from Eq. 6 and defining $f_{hi} \equiv d_{hi}/a = \tilde{n}_{lo}/(\tilde{n}_{lo} + \tilde{n}_{hi})$, we can further generalize Eq. 6 to give:

$$\text{fraction of } \int \left| \bar{E}^2 \right| \text{ in cladding for } TE_{01} \propto \frac{f_{hi}^2}{\left(1 - \kappa_{te}^2\right)} \frac{a^3}{R^3} \qquad (16)$$

Similarly, Eqs. 12 and 13 can be further generalized, where we also define

$\bar{n} \equiv \left(n_{hi} - n_{lo}\right) f_{hi} + n_{lo}$:

$$TE_{01} \text{ cladding absorption} \propto \frac{\bar{n} f_{hi}^2}{\left(1 - \kappa_{te}^2\right)} \frac{a^3}{R^3} \qquad (17)$$

$$TE_{01} \text{ cladding nonlinearity } \frac{\gamma}{\gamma_0} \propto \frac{\bar{n} f_{hi}^4}{\left(1 - \kappa_{te}^4\right)} \frac{a^5}{R^5} \qquad (18)$$

The number of cladding layers required to achieve a given radiation leakage rate for TE or TM modes scales inversely with log $(1/\kappa_{te})$ or log $(1/\kappa_{tm})$, respectively. So, for example, if one used indices of 1.459/1.450, as may be common for doped silica layers, about 2000 cladding layers are required to achieve the same TE radiation-leakage rates as in Figure 6.

The bandwidth also varies with index contrast. One is limited by the size of the TM gap along the light line, which for the quarter-wave stack of Eq. 4 is:

$$\frac{\Delta \omega_{TM}}{\omega_0} = \frac{4}{\pi} \sin^{-1} \left(\frac{n_{hi}^2 \bar{n}_{lo} - n_{lo}^2 \bar{n}_{hi}}{n_{hi}^2 \bar{n}_{lo} + n_{lo}^2 \bar{n}_{hi}} \right) \qquad (19)$$

where ω_0 is the mid-gap frequency:

$$\omega_0 = \frac{\bar{n}_{lo} + \bar{n}_{hi}}{4 \bar{n}_{lo} \bar{n}_{hi}} \cdot \frac{2\pi c}{a} \qquad (20)$$

Telecommunication Systems

The photonic crystal waveguides described herein may be used in optical telecommunications systems. Figure 11 shows a schematic diagram of an optical telecommunication system 1100 including a source node 1100 and a detection node 1120, which are coupled to one another by an optical transmission line 1130. The optical

transmission line may include one or more segments of transmission fiber 1132 and one or more segments of dispersion compensation fiber 1134. Source node 1110 may be the original source of an optical signal directed along the transmission line or it may be an intermediate node that redirects the optical signal to transmission line 1130, optically amplifies it, and/or

5 electronically detects it and optically regenerates it. Furthermore, source node 1110 may include components for multiplexing or demultiplexing multiple optical signals at different wavelengths. Similarly, detector node 1120 may be the final destination for the optical signal transmitted along the transmission line, or it may be an intermediate node that redirects, optically amplifies, and/or electrically detects and optically regenerates the optical signal. In

10 addition, detector node 1120 may also include components for multiplexing or demultiplexing multiple optical signals at different wavelengths. The dispersion compensation fiber(s) may be positioned to pre-compensate, post-compensate, or inline compensate for dispersion in the optical signal caused by the transmission fiber(s). Furthermore, the optical signal transmitted along the transmission line may be a WDM signal that includes multiple signals at

15 corresponding wavelengths. Suitable wavelengths for the system include those within a range of about 1.2 microns to about 1.7 microns, which corresponds to many long-haul systems in use today, as well those within a range of about 0.7 microns to about 0.9 microns, which corresponds to some metro systems currently being considered.

Because of their small losses and nonlinearities, the large core photonic crystal fibers

20 described herein may be used as the transmission fiber in system 1100. Because the losses are small, the lengths of the transmission line can be made larger as periodic amplification is less necessary. For example, the losses may be smaller than 1dB/km, smaller than 0.1 dB/km, or even smaller than 0.01 dB/km. Moreover, because FWM is reduced, WDM channel spacing in the fiber can be made smaller. Furthermore, large amounts of dispersion may be compensated

25 by dispersion compensating fiber 1134 because the nonlinear length scales are much smaller.

Coupling Issues

Finally, we briefly address coupling between the large core photonic crystal fibers described herein and adjacent fibers and/or optical systems connected at their respective ends.

30 Generally, the coupling efficiency between respective modes of fibers connected to one another is proportional to the degree to which a mode in the first fiber overlaps spatially with a

mode in the second fiber. In the photonic crystal fibers described herein, the lowest-loss mode is typically associated with the TE_{01} mode. Accordingly, for applications where the photonic crystal fiber has a long length, operating with the TE_{01} mode is preferable. The TE_{01} mode has an azimuthal symmetry and has an electric field distribution that is maximized at a distance

5   from the core center. On the other hands, index-guided silica fibers usually operate with the doubly degenerate HE_{11} mode (which may correspond to, for example, linearly polarized light at the core center). Such a mode may not overlap well with the TE_{01} mode, which has an azimuthal symmetry and has an electric field distribution that is maximized at a distance from the core center.

10   To facilitate coupling, either fiber may include a mode-coupling region to optimize coupling between a first mode in a first fiber and a second mode in a second fiber. For example, to couple an $m=1$ working mode from a photonic crystal fibers described herein to the HE_{11} mode of silica optical fiber, the silica fiber may include a mode coupling region whose index cross-section changes with axial position to smoothly couple the working mode to the

15   HE_{11} mode. In one example, the coupling region may have a hollow ring-shaped cross-section that index-guides light within the ring cross-section and subsequently fills in along the axial direction to form a conventional optical fiber. The ring diameter and thickness would be selected to optimize coupling from the working mode, whose field distribution is maximized at some distance from the core center. In another example, the cross-section of the silica fiber in

20   the coupling region could be doped with impurities to optimize coupling, e.g., the doping could form a ring-shaped pattern. The doping pattern would gradually be phased out over the axial extent of the coupling region. Furthermore, in other embodiments, it may be the photonic crystal fiber that includes the coupling region with some axial variation in refractive index cross-section.

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A number of embodiments of the invention have been described. Nevertheless, it will be understood that various modifications may be made without departing from the spirit and scope of the invention. Accordingly, other embodiments are within the scope of the following claims.

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